TRANSACTIONS OF THE 12TH CARIBBEAN GEOLOGICAL CONFERENCE

ST. CROIX, U.S. VIRGIN ISLANDS

August 7th - 11th, 1989

12a Conferencia Geologica del Caribe

12th Caribbean Geological Conference

St. Croix

7th - 11th August, 1989

U.S. Virgin Islands

12me Conference Geologique de Caraibes

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December 1990

STRATIGRAPHIC AND STRUCTURAL RELATIONSHIPS ON TOBAGO, WEST INDIES, AND SOME TECTONIC IMPLICATIONS

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ABSTRACT

Tobago is principally composed of igneous and metamorphic rocks that comprise a natural cross-section through a fragment of the allochthonous, Mesozoic oceanic-arc of the southern Caribbean. The pre-Cenozoic rocks of Tobago can be divided into four, approximately east-west-striking belts that transect the island: North Coast Schist (NCS), amphibolite-facies aureole (dynamothermal metamorphism of NCS rocks), ultramafic to tonalitic plutonic complex, and Tobago Volcanic Group (TVG). A mafic dike swarm widely intruded the plutonic complex and TVG, whereas only scattered post-metamorphic dikes occur in the NCS and amphibolite-facies aureole belts.

Radiolaria in argillite layers from a distinctive epiclastic unit in the TVG suggest an Aptian-Albian age, and ammonite molds from the same unit indicate an Albian age. $^{40}Ar/^{39}Ar$ hornblende plateau ages from the plutonic-volcanic-dike complex indicate that this rock suite evolved principally during the Albian (ca 105-103 Ma). One representative of the mafic dike swarm yielded a hornblende plateau age of ca 91 Ma, indicating that mafic magmatism apparently extended into the early Late Cretaceous. The age of the NCS is at least Aptian and perhaps as old as Late Jurassic ($^{40}Ar/^{39}Ar$ data on relict igneous hornblende from greenschist-facies tuff breccia).

Quaternary coralline limestone forms a low relief platform at the southwestern end of the island. Other Cenozoic map units are the Rockly Bay Formation (Pliocene), sandstone, conglomerate, and limestone of Montgomery (Pleistocene to Pliocene?), and Quaternary alluvium.

The NCS rocks are lower greenschist facies, multiply-deformed volcanogenic rocks. Detailed geologic mapping indicates that the NCS was wallrock for the plutonic complex. A selvage of amphibolitic rocks (<250 m structural thickness) forms a mappable belt between the NCS and the plutonic complex. Metamorphic grade in the aureole decreases with increasing structural depth, thereby exhibiting an inverted metamorphic gradient. The primary igneous contact between the intrusive plutonic rocks and the metamorphosed NCS rocks is only locally preserved, and more commonly this boundary has been overprinted by brittle deformation and retrogression. Where preserved, the primary igneous contact is interpreted as the margin of a zone of high shear strain which developed as a hot, nearly crystallized mass of ultramafic-mafic rocks dynamothermally metamorphosed older greenschist facies rocks during emplacement into the upper crust. During the progressive upward emplacement of the plutonic suite, this zone evolved from a plastic shear zone into a brittle fault zone referred to here as the "back-aureole (reverse) fault". Although the back-aureole fault virtually transects the island, it is related to the emplacement of the intrusive plutonic complex and not a regional compressive stress regime. Furthermore, in that this fault zone appears to have developed in close association with the mid-Cretaceous plutonic suite, it is inferred to be a Cretaceous fault system.

Both normal and oblique-slip faults have fragmented and offset the back-aureole fault. A normal fault system subparallel to the back-aureole fault has greatly complicated relationships by attenuating the amphibolite aureole and juxtaposing various elements of the four main belts into anastomosing, fault-bounded slices. A still younger system of high-angle, cross-cutting faults strike approximately NNW and chiefly display left-lateral separation. This separation is probably a result of a complex oblique-slip displacement history. The age of the normal and oblique-slip faulting is uncertain but may be related to the broad strike-slip regime that apparently existed in the southeastern Caribbean during the Neogene.

Tobago is the easternmost part of a composite oceanic-arc terrane that initially collided with the northwestern margin of South America in the mid-Late Cretaceous. Subsequently, parts of this allochthonous terrane were progressively accreted from west to east along the northern rim of South America. Displaced fragments of the originally composite, Mesozoic oceanic-arc preserved in the southeastern Caribbean include: the Aruba-Blanquilla island chain, Aves Ridge, the Villa de Cura klippe (Venezuela), the El Copey Formation (Araya Peninsula), and Tobago, West Indies.

INTRODUCTION

Tobago, West Indies, is an island that forms part of a structural high composed chiefly of Mesozoic igneous and metamorphic rocks at the northeasternmost corner of the present-day South American continental shelf (Figure 1; Case and

Larue, D.K., and Draper, G. (eds.), ***Transactions of the 12th Caribbean Geological Conference, St. Croix, U.S.V.I.***, Miami Geological Society, P.O. Box 431552, South Miami, FL 33243, U.S.A

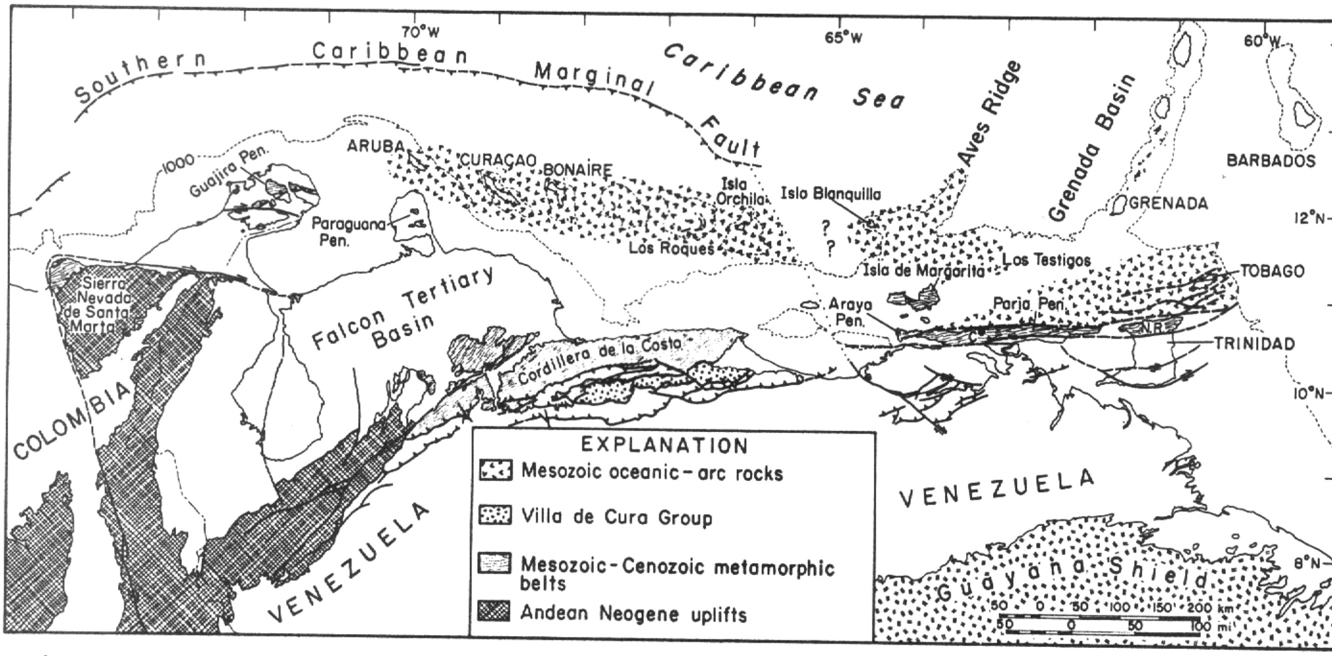

Figure 1. Regional geotectonic map of the southern Caribbean region showing the inferred distribution of fragments of the accreted Mesozoic oceanic-arc and associated geological terranes. N.R. = Northern Range. C = Carúpano.

Holcombe, 1980). However, petrochemical data indicate an oceanic island arc character (Frost and Snoke, 1989), implying an allochthonous history since petrogenesis. Tobago, therefore, has a definite affinity with allochthonous oceanic-arc rocks that occur as scattered fragments along the northern rim of South America (e.g., Stephan et al., 1980; Figure 1). It is thus the easternmost element of the Caribbean Mountain system (Bellizzia, 1972). Tobago's position and relationships with the southern Lesser Antilles island arc and associated accretionary prism are more uncertain, and have prompted substantial speculation. Could the Paleogene platform of the southern Lesser Antilles volcanic arc be built upon a Mesozoic igneous and metamorphic basement similar to Tobago (Westbrook and McCann, 1986; Bouysse, 1988)? Is Tobago part of an accretionary complex that is obliquely overriding the northeast continental margin of South America (Speed, 1985, 1986; Speed and others, 1989)? Is Tobago a fault-bounded sliver that has been transported hundreds of kilometers along the Caribbean-South American plate boundary (Robertson and Burke, 1988)?

Obviously, a detailed knowledge of the geologic history of Tobago would provide some important constraints for these and other tectonic models for the southeastern Caribbean. The purpose of this article is therefore to present a preliminary overview of the stratigraphic and structural relationships of the Mesozoic rocks exposed on Tobago, West Indies, and to highlight the implications of these relationships for the tectonostratigraphic history of the allochthonous, Mesozoic oceanic-arc of the southern Caribbean.

We begin our overview with descriptions of the broad-scale subdivisions of the Mesozoic igneous-metamorphic complex of Tobago (Table 1); the distribution of these rock units is shown on Figure 2. A summary of new $^{40}Ar/^{39}Ar$ radiometric studies (Table 2) which provides important geochronological constraints on the evolution of the Mesozoic rock suite is also presented. In the second part of the article, we summarize the main structural features of the island, and two geologic cross-sections (Figure 3) allow one to visualize these relationships at depth. Finally, these data, analyzed within the regional framework of the southern Caribbean, are used to provide a preliminary evaluation of four fundamental aspects of the geology of Tobago:

1) the cogenetic nature of the mid-Cretaceous plutonic and volcanic rocks on Tobago;

2) the development of a composite oceanic island-arc terrane;

3) the affinity of the Tobago terrane to other lithological units in the southern Caribbean; and

4) the displacement history of the Tobago terrane.

ROCK UNITS

The Mesozoic rocks of Tobago (Table 1) can be divided into four main groups: the North Coast Schist (NCS), amphibolite-facies aureole (dynamothermal metamorphism of the NCS rocks), the ultramafic to tonalitic plutonic complex, and the Tobago Volcanic Group (TVG). These broad lithologic subdivisions form approximately east-west-striking belts which transect the island (Maxwell, 1948). A mafic dike swarm widely intruded the plutonic complex and TVG, whereas only scattered post-metamorphic dikes occur in the NCS belt. The Mesozoic rocks of Tobago represent an exceptional natural cross-section through a part of a composite oceanic-arc terrane (Frost and Snoke, 1989).

A systematic $^{40}Ar/^{39}Ar$ study was carried out

TABLE 1. LITHOLOGIC SUBDIVISIONS OF PRE-CENOZOIC ROCKS OF TOBAGO, WEST INDIES

I. North Coast Schist (inferred stratigraphic order, oldest to youngest)

Parlatuvier Formation - intermediate to mafic tuff and tuff breccia, and pre-metamorphic andesite dikes

Mt. Dillon Formation - siliceous tuff (locally silicified), graphitic siliceous schist, graphitic quartzose phyllite, chert, and scarce premetamorphic andesite dikes

II. Tobago Volcanic Group [stratigraphic order uncertain, apparent order oldest to youngest given; the designations of Maxwell (1948) in parentheses]

Hornblende + plagioclase + clinopyroxene-phyric tuff breccia and lapilli tuff

Plagioclase + clinopyroxene-phyric tuff breccia, lapilli tuff and lava (Goldsborough and Hawk's Bill formations)

Argillite (contain Aptian(?)-Albian radiolaria and Albian ammonites) and volcaniclastic breccia, grit, and sandstone

Clinopyroxene + plagioclase-phyric tuff breccia, lapilli tuff, and scarce lava (Bacolet and Merchiston formations)

III. Plutonic complex (oldest to youngest, based on intrusive relations)

Older deformed mafic plutonic-volcanic complex

Dunite, wehrlite, olivine clinopyroxenite, hornblendite, hornblende plagioclase pegmatoid

Hornblende ± clinopyroxene gabbro, diorite, quartz diorite

Biotite ± hornblende tonalite

IV. Mafic dike swarm (chiefly intrudes plutonic complex and Tobago Volcanic Group but also common in the amphibolitic aureole; only scattered post-metamorphic dikes in the North Coast Schist)

Hornblende microdiorite, hornblende gabbro, acicular hornblende-phyric diorite, dolerite, hornblende + clinopyroxene-phyric melagabbro.

during geologic mapping and structural analysis of Tobago. A detailed report analyzing these new data is in preparation (Sharp and Snoke, in prep., 1990). However, as a chronological framework for this article, we have prepared a brief summary of the new radiometric data (Table 2). These data indicate the following age constraints:

1) $^{40}Ar/^{39}Ar$ hornblende dates from the volcanic-plutonic complex indicate a contemporaneous magmatic evolution in the mid-Albian (ca 103-105 Ma);

2) Hornblende plateau ages from the mafic dike suite indicate two emplacement ages: early dikes, only slightly younger (ca 102-103 Ma) than the volcanic-plutonic complex and a distinctly younger suite (ca 91 Ma); and

3) a primary protolith age on the volcanogenic Parlatuvier Formation of the North Coast Schist >120 Ma.

The Cenozoic rock record on Tobago, exclusive of Holocene surficial deposits, consists of the following deposits (oldest to youngest): Rockly Bay Formation (Pliocene); sandstone, conglomerate, and limestone of Montgomery [Pleistocene - Pliocene(?)]; and the coralline limestone of Booby Point (Quaternary). These deposits represent various shallow marine accumulations and their preservation therefore records tectonic uplift and/or sea level change. These shallow marine deposits are conspicuously fossiliferous and consequently several studies have been completed on these rocks (for specific details see: Trechmann, 1934; Maxwell, 1948; Saunders and Muller-Merz, 1985). The distribution of these deposits is shown in Figure 2.

North Coast Schist

This extensively exposed rock unit forms the northern third of the island, including the rugged and densely vegetated backbone of Tobago known as the Main Ridge. This lithologically diverse and strongly deformed unit was named by Maxwell (1948) and differs significantly from the schistose rocks of the Northern Range of Trinidad because it has evolved from volcanogenic protoliths (Rowe and Snoke, 1986). The NCS rocks were pervasively

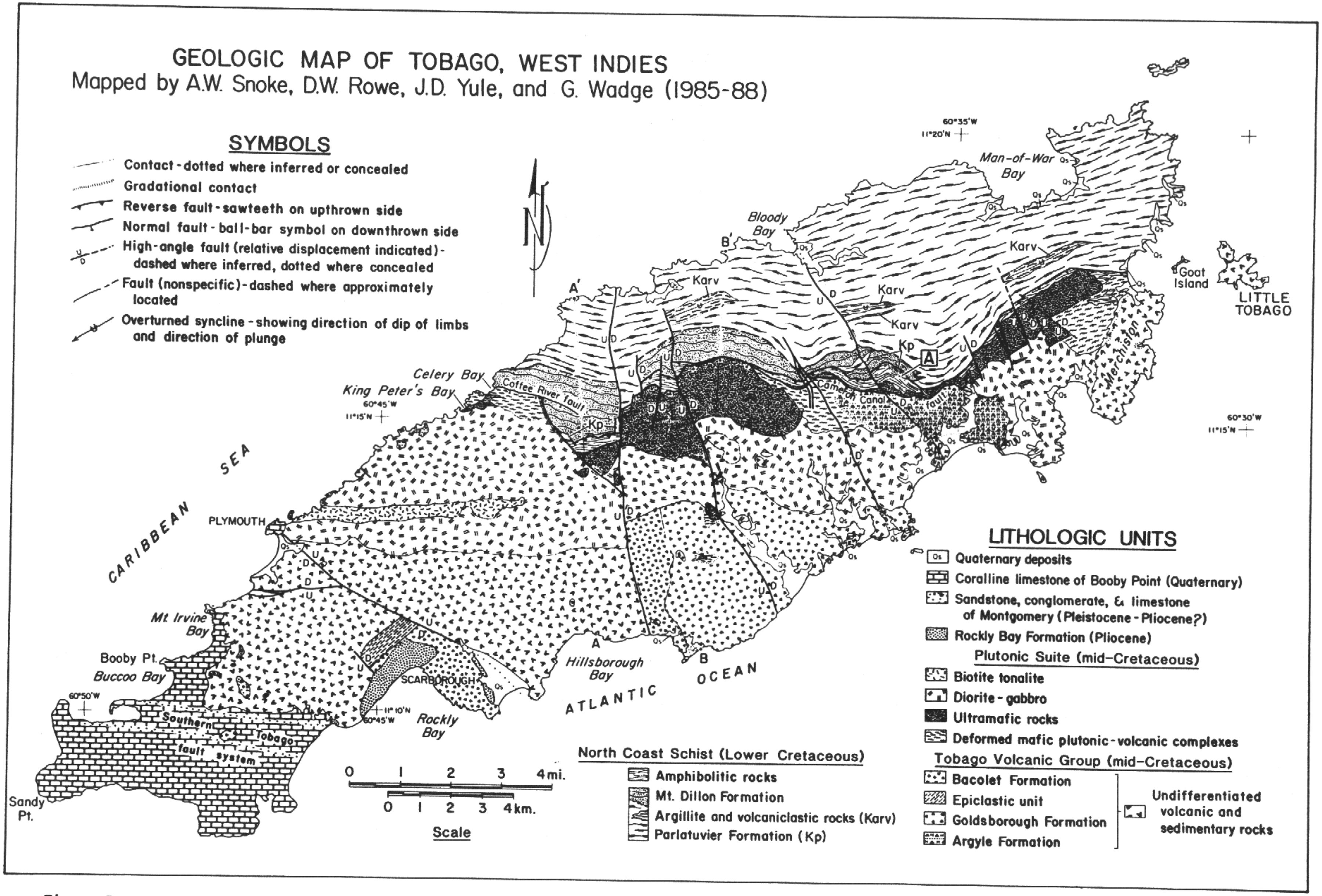

Figure 2. Geologic map of Tobago, West Indies.

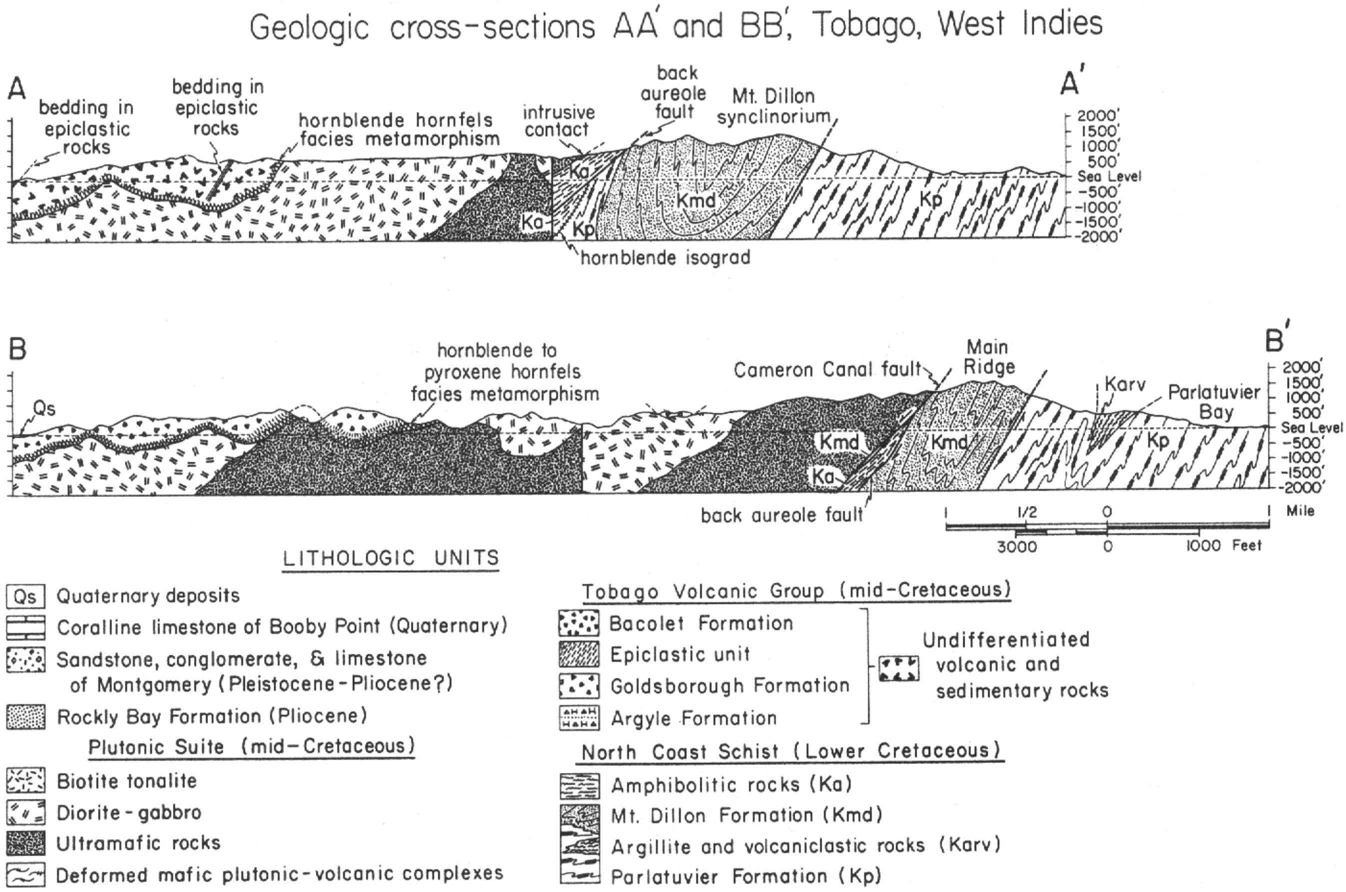

Figure 3. Geologic cross-sections across Tobago, West Indies.

metamorphosed during the mid-Mesozoic (Sharp and Snoke, 1988) and ubiquitously contain lower greenschist-facies mineral assemblages (e.g., chlorite, epidote, actinolite, and albite in mafic protoliths). Along its southern margin, the NCS has been intruded by the ultramafic rocks of the plutonic suite thereby transforming the greenschist-facies rocks to a much higher metamorphic grade characterized especially by the development of hornblende and more calcic plagioclase (oligoclase and andesine). This distinct belt of hornblende schists can be mapped virtually across the island and is referred to as the "amphibolite-facies aureole". These hornblende schists locally grade into typical greenschist-facies NCS rocks, but more commonly, a reverse fault (i.e., the so-called "back-aureole" fault) forms the boundary between the NCS and the strongly metamorphosed and deformed rocks of the amphibolite aureole.

Although the NCS is unfossiliferous, field relationships coupled with radiometric dating indicate that the NCS is apparently the oldest rock unit exposed on the island. As noted above, the NCS served as wallrock for the younger plutonic suite. Furthermore, $^{40}Ar/^{39}Ar$ radiometric dating of relict igneous hornblende from the NCS indicates a pre-Aptian protolith age (>120 Ma) and perhaps as old as Late Jurassic (Table 2).

We have recognized two fundamental lithologic facies that constitute the NCS: Parlatuvier Formation= basaltic andesite lapilli tuff and crystal-lapilli tuff and associated subvolcanic mafic intrusives, and Mt. Dillon Formation= dacitic crystal-lapilli tuff, volcanogenic argillite and siliceous argillite, and siliceous hydrothermal replacement deposits (volcanogenic chert, originally designated "quartzite" by Maxwell, 1948). Although these rocks have been metamorphosed and locally intensely deformed, relict volcanic textures are locally very well-preserved. Coarse volcaniclastic tuff breccia in the Parlatuvier Formation is especially spectacular, consisting of large lithic clasts (sometimes > 30 cm across) in a fine-grained matrix of albite, quartz, epidote, chlorite, calcite, and various accessory minerals.

The Parlatuvier Formation comprises the majority of the NCS, and fresh samples always possess a distinctive dark green to gray-green hue (i.e., a manifestation of the greenschist facies mineral phases). The Mt. Dillon Formation is chiefly exposed in the southern and western parts of the NCS (Fig. 2). This unit is characteristically more siliceous than the Parlatuvier, including both tuffaceous and sedimentary rocks, and when fresh, hand specimens are characterized by dark grayish hues. Weathered massive buff-colored tuff is also very distinctive of the unit, especially in roadcuts or along trail exposures.

The volcaniclastic protoliths of the NCS represent a rock suite deposited subaqueously in a basin adjacent to a volcanic arc. Proximal coarse-grained tuff breccia and crystal-lapilli tuff

TABLE 2. A SUMMARY OF $^{40}Ar/^{39}Ar$ RADIOMETRIC AGE DATA, TOBAGO, WEST INDIES

All ages are based on $^{40}Ar/^{39}Ar$ incremental heating analyses of hornblende. Age assignments are based on consideration of age spectra, K/Ca ratios of individual gas fraction, and isotope correlation diagrams as well as the geologic history of the samples.

Sample 2D-14: A 1-meter-wide dike of hornblende gabbro which intrudes biotite tonalite yielded a plateau age of 91.4±2.2 Ma, interpreted as the age of igneous crystallization.

Sample 1C-30: A 1-meter-wide dike of hornblende melagabbro which intrudes biotite tonalite yielded a plateau age of 102.9±1.1 Ma, interpreted as the age of igneous crystallization.

Sample 1C-29: A 2-meter-wide dike of hornblende porphyry which intrudes biotite tonalite yielded a plateau age of 102.8±1.2 Ma, interpreted as the age of igneous crystallization.

Sample 1C-5: Poikilitic hornblende (quartz-bearing) diorite, a phase of the gabbro-diorite pluton yielded a linear array on an isotope correlation diagram indicating an age of 104.7±1.6 Ma, corresponding to its age of igneous crystallization.

Sample 2D-35: A dikelet of hornblende gabbro pegmatite, representing a late, water-rich phase of the clinopyroxene-rich ultramafic rocks of the intrusive plutonic suite yielded a linear array on an isotope correlation diagram indicating an age of 103.6±1.4 Ma, corresponding to its age of igneous crystallization.

Sample T827: A lithic clast of hornblende-plagioclase porphyry from the Tobago Volcanic Group yielded a plateau age of 104.2±1.3 ma, corresponding to the eruptive age of the enclosing volcaniclastic strata.

Sample DR245: Relict igneous hornblende from a clast of hornblende-phyric andesite in a tuff from the greenschist facies North Coast Schist yielded a complex release spectrum indicating an igneous age of ≥120 Ma.

Low temperature parts of release spectra from several samples interpreted to contain intergrowths of phyllosilicates yield ages of about 92 Ma, interpreted to indicate that cooling below about 280°C took place by this time.

(Parlatuvier Formation) interfinger with more distal, fine-grained tuff and hemi-pelagic sedimentary rocks (Mt. Dillon Formation). A possible modern analog of the depositional environment of the NCS is the depositional setting of volcanogenic deposits of the Lesser Antilles island arc in the Grenada basin where coarse, subaqueous pyroclastic debris-flow deposits interfinger with fine-grained basinal facies sediments (Sigurdsson and others, 1980).

Ultramafic to tonalitic plutonic complex

A heterogeneous suite of plutonic rocks forms an intrusive complex immediately south of the NCS. These plutonic rocks have intruded and dynamothermally metamorphosed the NCS wallrocks, and roof pendants of TVG rocks form a south-dipping carapace above the intrusive complex.

The plutonic suite consists of four mappable units: 1) deformed and metamorphosed mafic rocks; 2) ultramafic rocks; 3) gabbro-diorite; and 4) biotite tonalite. Unit 1) was penetratively deformed under hornblende-hornfels to pyroxene-hornfels facies metamorphic conditions during the emplacement of adjacent intrusive ultramafic masses. The protolith for this deformed oldest unit ranged from porphyritic gabbroic bodies to mafic fragmental volcanic rocks (i.e., TVG). The ultramafic rocks form several discontinuous lenticular masses that can be mapped across the island. The ultramafic rocks are commonly clinopyroxene-rich, varying from wehrlite to hornblende clinopyroxenite; however, locally dunite forms distinct masses within the ultramafic complex. Orthopyroxene has not been recognized as a pyrogenetic phase in these ultramafic rocks, and the rocks are not tectonites. These characteristics clearly suggest an affinity with Alaskan-type ultramafic-mafic complexes rather than ophiolitic suites (Snoke et al., 1982). These ultramafic rocks are interpreted as crystal accumulations that were segregated during magmatic differentiation of an originally basaltic magma in a mid-crustal magma chamber. Subsequently, the crystal-rich portions of the magma chamber were re-mobilized and emplaced higher in the crust as hot, nearly solid crystal aggregates. The emplacement of these hot crystal-rich aggregates caused intense deformation of the wallrocks. The NCS was dynamothermally metamorphosed at amphibolite-facies conditions (i.e., the amphibolite-facies aureole), and older parts of the plutonic complex (e.g., unit 1) were also metamorphosed and deformed adjacent to the ultramafic masses. A heterogeneous gabbro-diorite unit subsequently intruded both units 1 and 2, and forms the most extensive plutonic unit on the island. Variations in mineral content and texture of the gabbro-diorite unit are extreme; compositionally the plutonic rocks of this unit range from quartz diorite to melagabbro, texturally from uniform, medium-grained to pegmatitic. In many parts of the gabbro-diorite unit, extreme textural and compositional variations are common in a single set of exposures, although locally the gabbro-diorite unit can also be strikingly homogeneous. The youngest unit in the plutonic suite is biotite +/- hornblende tonalite that forms an EW-striking, dike-like body that has been mapped from the Caribbean coast near Plymouth to its exposed surface end about 7 1/2 km inland (Fig. 2). Analysis of aeromagnetic data suggests that this intrusion may continue in the subsurface at least several kilometers east of its surface termination (Wadge and Snoke, in prep.).

Tobago Volcanic Group

The volcanic rocks (TVG) that form a carapace above the plutonic suite can be traced from Rocky Point to Little Tobago island (Fig. 2). Cupolas of mafic and ultramafic plutonic rocks locally intrude the volcanic rocks indicating the proximity of the plutonic body beneath the volcanic carapace (Figs. 2, 3). The thickest section of the TVG is exposed near Scarborough where a generally poorly-exposed stratigraphic section of TVG rocks dip moderately (ca 40-50^{o}) to the southeast. In this section, a fossiliferous epiclastic unit has been delineated (Fig. 2). This unit consists of black argillite, sandstone, and sedimentary breccia. Radiolaria in the argillite suggest an Aptian-Albian age (P. Noble, per. comm., 1990), and ammonite molds from several horizons in this unit indicate an Albian age (W.A. Cobban, pers. comm., 1988). Hornblende from TVG tuff breccia collected on Little Tobago island has yielded a plateau age of ca 104 Ma, indicating an Albian age also for this part of the TVG (Table 2).

The TVG rocks are chiefly volcaniclastic breccias, ranging from block-and-ash flow deposits to subaqueous debris-flow deposits; however, locally lava (sometimes pillowed) forms prominent accumulations in the volcanic pile. These volcanic rocks were probably deposited on the flanks of a submarine volcanic center. The following characteristics support a proximal submarine depositional history:

1) pillowed lavas (submarine eruption of lava);

2) the intercalation of marine sedimentary rocks (i.e., fossiliferous argillite);

3) the coarse fragmental texture of much of the rock units;

4) the absence of virtually all non-volcanogenic material;

5) extensive metasomatic alterations (Jackson and Smith, 1985; and Frost and Snoke, 1989).

The laterally discontinuous sedimentary sequences may represent local "ponded" basins along the flanks of the volcanic arc that accumulated hemipelagic and epiclastic sediments between the volcanic eruptions.

Mafic dike swarm

Numerous mafic dikes intrude the plutonic suite and TVG rocks. The most common mafic dikes are fine-grained with microscopic acicular hornblende and subequant plagioclase. The dikes are tabular bodies that form distinctive dark-colored bands in the older plutonic or volcanic wallrock and commonly range in width from about 15 centimeters to a meter. $^{40}Ar/^{39}Ar$ radiometric dating on hornblende from representative samples of the mafic dike swarm indicate two distinct episodes on dike injection. The early, and perhaps most widespread, phase is ca 103 Ma, whereas one member of the dike swarm has yielded a hornblende plateau age of ca 91 Ma.

STRUCTURAL FEATURES

Deformational history of the NCS

Strong penetrative plastic deformation accompanied the greenschist facies metamorphism of the NCS. These volcanogenic rocks were converted into foliated and lineated metamorphic tectonites. Mesoscopic structural features in the NCS include: two foliation surfaces (S_1 and S_2), four fold generations [F_1, F_2 (see Fig. 4), chevron, and kink bands], a stretching lineation (L_{str}), and three intersection lineations (L_{0x1}, L_{0x2}, L_{1x2}). S>L- or S-tectonites are most common, but L>S- or L-tectonites are locally conspicuous. All these features, except perhaps some of the angular folds, were formed during a continuous deformational history that pre-dated the evolution of the mid-Cretaceous plutonic-volcanic-dike complex.

The primary foliation surface in the NCS is S_1 defined in part by the planar orientation of platy metamorphic minerals such as chlorite and white-mica or tectonically flattened volcanogenic fragments (i.e., lapilli). S_1 is subparallel to the axial surfaces of F_1 folds (synmetamorphic) which dip southward across the island. These folds plunge gently to moderately NE-ENE or SW-WSW, but verge consistently northward (i.e., toward the Caribbean Sea). The stretching lineation (L_{str}) is subparallel to the hingelines of the F_1 folds and therefore also plunges gently to moderately NE-ENE or SW-WSW. The hingelines of F_2 folds (late metamorphic) are also broadly subparallel to the hingelines of F_1 folds and the stretching lineation. Therefore, this common coaxiality of fabric elements is interpreted to indicate that both the synmetamorphic and late metamorphic fold phases and the stretching lineation developed during the same progressive, polyphase deformation. Sheath folds have not been recognized in the NCS, and many of the F_1 folds are near-cylindrical in form. The full kinematic significance of these relationships is not fully understood; but it appears likely that the F_1 folds were not rotated into parallelism with the stretching lineation. The folds and stretching lineation evolved concurrently during a period of complex plastic deformation with a strong extensional component parallel to the stretching lineation (i.e., X axis of the finite strain ellipsoid). The overall orientation of the stretching lineations and not the vergence of the folds is the best indicator of the slip line during this plastic deformation.

Deformational features within the amphibolite-facies aureole

The amphibolite aureole occurs as a largely continuous, narrow strip between the NCS and the intrusive plutonic complex (Fig. 2). Where absent, the aureole has been truncated by a NW-striking, right-lateral, oblique-slip(?) fault (Fig. 2). Metamorphic grade within the aureole decreases with

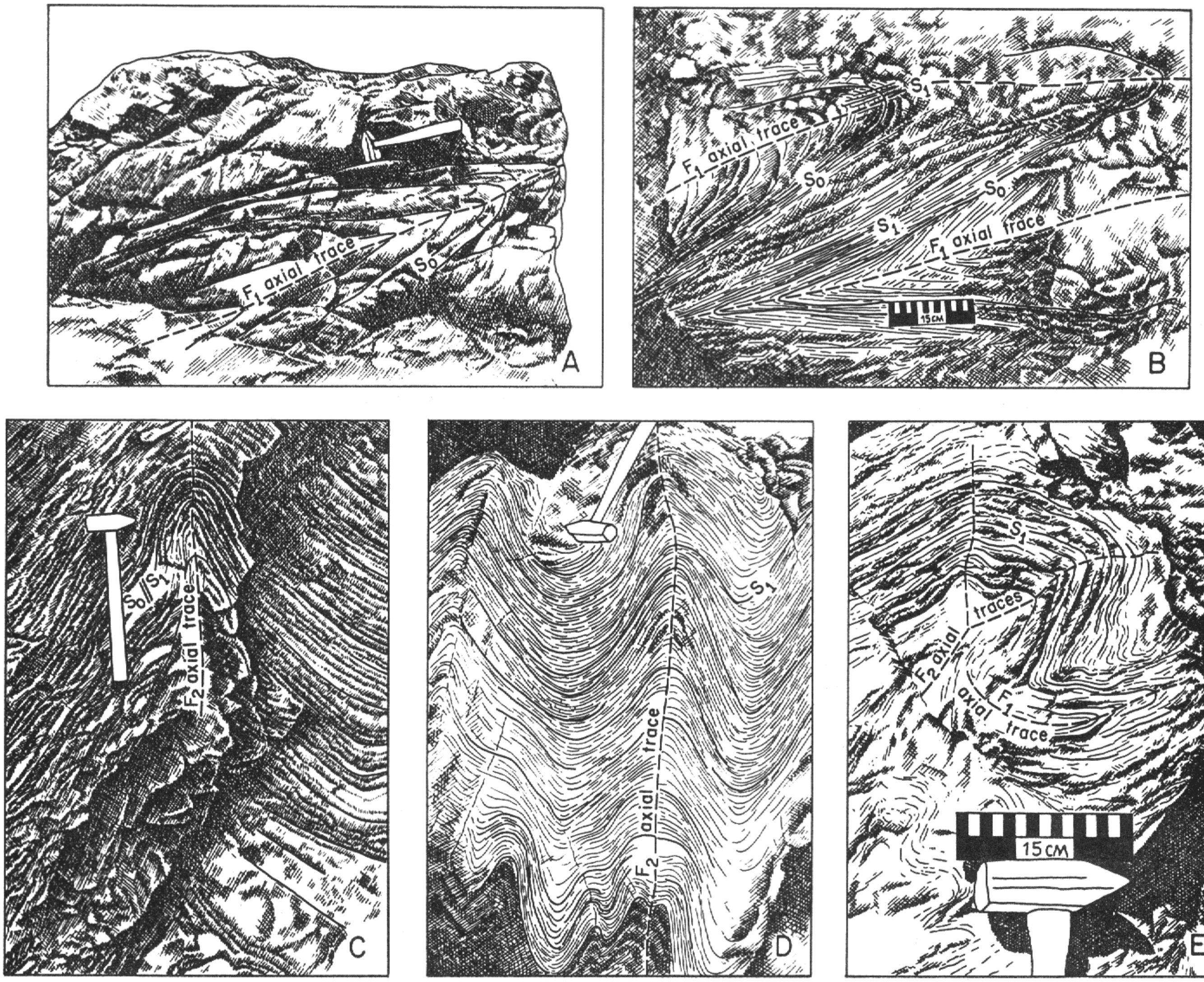

Figure 4. Fold styles in the North Coast Schist. A, S_o, original bedding in the Parlatuvier Formation, deformed by a F_1-style fold, S_1 cleavage subparallel to the F_1 axial surface, Dead Bay River; B, F_1-style, "Z-shaped" fold in the Mt. Dillon Formation, Mt. Dillon trace, note the convergence of S_1 cleavage near the lower hinge; C, Upright, F_2-style fold that deformed both S_o and subparallel S_1 foliation in the Parlatuvier Formation, roadcut along dirt road (Northside Road) approximately 1.3 km northeast of Anse Fourmi; D, S_1 foliation folded by upright, F_2-style flexural flow folds in the Parlatuvier Formation, Bloody Bay River; E, Late F_2-style boxfold that refolded a F_1-style isoclinal fold in the Parlatuvier Formation, Englishman's Bay. Sketches by Phyllis A. Ranz from photographs by A.W. Snoke.

increasing structural depth, thereby exhibiting an inverted metamorphic gradient. The inner parts of the aureole are characterized by a black to gray, locally gneissic, intensely foliated and lineated amphibolite. Toward the outer part of the aureole, the rocks are gray-green to green, epidote-rich, and the intensity of the penetrative fabric is less conspicuous. The northern boundary of the aureole is the "back-aureole" reverse fault which typically truncates amphibolite-facies aureole rocks emplacing them directly adjacent to greenschist-facies Parlatuvier or Mt. Dillon formations. However, in one area, the amphibolite-facies rocks gradually grade into lower greenschist-facies metavolcanic rocks characteristic of the Parlatuvier Formation (Figure 2, locality A). The back-aureole fault in turn truncates these greenschist-facies Parlatuvier rocks, emplacing them above greenschist-facies Mt. Dillon Formation. The protolith for the rocks of the amphibolite-facies aureole therefore is interpreted as the Parlatuvier Formation, albeit on the overturned limb of the Mt. Dillon synclinorium (Fig. 3, section AA').

Structural elements of the aureole include a synmetamorphic foliation and mineral lineation, and a post-metamorphic open fold phase. The foliation is defined by the planar alignment of hornblende and plagioclase grains and locally by alternating hornblende-rich and plagioclase-rich segregation layers. On the foliation plane, a mineral lineation defined by elongate hornblende and plagioclase grains is common. The orientation of the foliation varies but commonly strikes subparallel to the inferred strike of the contact with adjacent intrusive plutonic rocks and dips beneath the plutonic complex. The azimuth of the lineation is also variable but commonly plunges gently to moderately down the dip of the foliation (i.e., to the south or southeast).

Brittle fault systems

Brittle faults of variable slip delineate several fault systems that have fragmented the Mesozoic lithic belts of Tobago. The oldest fault system is a high-angle, reverse fault that commonly forms the northern contact of the amphibolite-facies aureole. The trace of this fault is closely associated with the greenschist-amphibolite metamorphic facies transition within the aureole, consequently, the fault's displacement history appears linked with the emplacement of the plutonic suite. Our interpretation of these relationships is that a high-temperature, plastic shear zone developed in NCS wallrocks (i.e., the amphibolite-facies aureole) marginal to intrusive ultramafic rocks. As the plutonic suite and its attached aureole rose higher in the crust, a distinct brittle, reverse fault formed in the transition zone between greenschist facies NCS rocks and amphibolite facies rocks of the aureole. This "back-aureole" reverse fault therefore evolved along the outer edge of the amphibolite aureole during the late stage emplacement history of the plutonic suite.

The back-aureole fault has been offset by both younger normal and oblique-slip faults. The best-studied normal faults are the Coffee River and Cameron Canal faults. Both strike approximately EW with hanging wall down to the south (Figs. 2 and 3). These normal faults that are subparallel to the trace of the back-aureole fault locally truncate it or re-use its fault surface in a normal-sense displacement. Both the back-aureole and normal faults are offset by north-northwest-striking high-angle faults. These faults are characterized by left-lateral separation. This separation is probably a result of a complex oblique-slip displacement history. The age of the normal and oblique-slip faulting is uncertain but may be related to the broad strike-slip regime that some geologists have suggested for the southeastern Caribbean during the Neogene (e.g., Robertson and Burke, 1988). A prominent NW-striking, high-angle fault does not fit this evolutionary history. Foliation and lithologic trends clearly indicate a dextral sense-of-slip for this fault. Furthermore, it truncates the back-aureole fault, but is truncated itself by the Coffee River normal fault. The NNW-striking faults also truncate this dextral-slip fault. Oblique-slip faulting therefore both predated and postdated normal faulting, but clearly postdated the development of the back-aureole fault. In this light, we tend to consider the back-aureole fault as Mesozoic, but all other brittle faults as Tertiary. These data suggest that brittle faulting commenced in the Cretaceous during the emplacement of the plutonic suite, but later faulting was superimposed on this system and involved a grossly different slip and probably stress regime.

Perhaps the youngest faults on Tobago are associated with the EW-striking Southern Tobago Fault System. Recurrent earthquake swarms beneath southern Tobago indicate that the system is active (Morgan et al., 1988). Stratigraphic correlations between onland boreholes suggested to Wadge and Hudson (1986) that at least two buried EW-striking faults with a down to the south sense-of-displacement were buried beneath the Quaternary limestone of Booby Point (uplifted coralline reef platform). A normal fault cutting Rockly Bay Formation in a sea cliff near Ju-C Beverages Bottlers Limited, Lower Scarborough, is oriented N85E 54°S and is the only known exposed fault cutting Cenozoic deposits. Immediately south of Black Rock village a distinct EW-striking topographic escarpment occurs within the TVG, and a zone of faults is mappable associated with the topographic break. Some of these faults may have an old and complex movement history, but late Neogene reactivation (south side up displacement) is a reasonable explanation for the escarpment. Significant lithologic contrasts across the fault zone that might suggest an origin of differential erosion for the topographic escarpment are absent. The late Neogene tectonic history of Tobago is poorly understood, but the island does lie within a complex tectonic belt that may serve as a transition zone from strike-slip faulting associated the Caribbean-South American plate boundary to subduction associated with the interaction of the southern Lesser Antilles and the Atlantic plate (Wadge and Hudson, 1986).

DISCUSSION

Cogenetic nature of the plutonic suite and the TVG

The new $^{40}Ar/^{39}Ar$ data (Table 2) coupled with recent paleontological discoveries (A.W. Snoke, W.A. Cobban, and P. Noble, unpublished data), new geochemical data (Frost and Snoke, 1989), detailed mineralogical studies (Girard, 1981), and the overall field relationships provide very strong support for Maxwell's (1948) hypothesis of broad contemporaneity between the TVG and the intrusive plutonic complex. Likewise, many members of the mafic dike swarm were consanguineous with the Albian volcanic-plutonic suite. However, one dike yielded a well-defined $^{40}Ar/^{39}Ar$ hornblende plateau age of ca 91 Ma (Table 2, sample 2D-14), clearly indicating that some mafic magmatism continued into the early Late Cretaceous. Late, broad-scale heating of this general age is also indicated by Ar-loss in the low temperature parts of release spectra for several samples (Table 2) and by fission-track zircon dates (P.F. Cerveny III and A.W. Snoke, unpublished data).

The TVG rocks occur as discrete roof pendants above the intrusive plutonic suite and cupolas of ultramafic to mafic rocks occur within the TVG suggesting that the plutonic suite underlies much of the TVG (Figures 2 and 3). Commonly the TVG rocks are only hornfelsic adjacent to contacts with the gabbro-diorite pluton. However, an enigmatic element of the volcanic-plutonic complex are discrete, highly deformed and metamorphosed complexes referred to on Figure 2 as "deformed mafic plutonic-volcanic complexes". Metamorphic mineral assemblages chiefly indicate hornblende-hornfels facies conditions, but locally pyroxene-hornfels facies assemblages (i.e., coexisting clino- and orthopyroxene) have been found in these metamorphosed mafic rocks (Yule, 1988). Based on detailed geologic mapping of gradational boundaries from weakly metamorphosed TVG rocks into the deformed and metamorphosed mafic complexes (Fig. 2) and relict igneous textures, the deformed mafic rocks appear to be early volcanic and hypabyssal components of the mid-Cretaceous volcanic-plutonic complex. These early mafic rocks were dynamothermally metamorphosed during the subsequent emplacement of the clinopyroxene-rich ultramafic rocks in much the same way that the NCS was metamorphosed to the amphibolite-facies aureole along its contact with the ultramafic rocks. Mafic dikes, a conspicuous component in both the TVG and plutonic suite, also are common in the "deformed mafic plutonic-volcanic complexes". A somewhat similar amphibolitized gabbroic suite was described by Irvine (1974) as surrounding the Alaskan-type, Duke Island ultramafic complex. Irvine (1974) interpreted this deformed mafic suite as metamorphosed wallrock for the younger ultramafic complex. As noted above, we also believe that the deformed mafic rocks were intruded and metamorphosed by intrusive, hot ultramafic rocks, but consider these deformed rocks as early phases of the volcanic-plutonic suite, whereas Irvine (1974) considered the amphibolitized gabbros as unrelated to the younger ultramafic complex.

The development of a composite Mesozoic oceanic-arc terrane

Nd isotopic data reported by Frost and Snoke (1989) clearly indicate an oceanic-arc petrogenesis for all pre-Cenozoic rocks exposed on Tobago. The NCS, the oldest and most deformed element of the oceanic-arc terrane, included metasedimentary rocks that suggested the involvement of no continental detritus during arc growth, whereas argillite from the younger TVG suggested an important continental contribution during arc growth. The mid-Cretaceous volcanic-plutonic complex is welded to the NCS along the amphibolite-facies aureole, and detailed structural and petrographic studies (Rowe, 1987; Yule, 1988; Yule et al., 1988) suggest that this boundary is a deformed intrusive contact and not a terrane boundary (i.e., suture). Therefore, we hypothesize that the pre-Cenozoic oceanic-arc rocks of Tobago represent a partial cross-section through a composite Mesozoic oceanic island arc. During the early stages of this arc [Late Jurassic(?) - Early Cretaceous], it was situated such that continental detritus was not involved in magma petrogenesis. During the mid-Cretaceous, the situation had apparently changed and a continental component was available during magma petrogenesis and arc growth. This important change in the involvement of continental detritus during arc growth may signal an important shift in the overall plate tectonic geometry related to the developmental history of the "Great Arc of the Caribbean" (Burke, 1988). The structural history of the inferred composite oceanic-arc terrane also suggests an important hiatus in arc growth. The NCS rocks were penetratively deformed under greenschist facies metamorphic conditions prior to the magmatic evolution of the mid-Cretaceous volcanic-plutonic complex. This history therefore suggests penetrative deformation within the Mesozoic oceanic-arc during its early developmental history. The tectonic regime under which this penetrative deformation occurred is uncertain; however, the strong subhorizontal, strike-parallel stretching lineation of the NCS suggests that a transpressive shear zone is a possible model. Deformation within such a shear zone must have pre-dated the mid-Cretaceous, for the TVG are only locally penetratively deformed. Furthermore, the local deformation of the TVG is interpreted as related to the emplacement of hot, partially crystalline ultramafic rocks and not a regional stress field. The mid-Cretaceous oceanic-arc suite therefore appears to be built on an older, deformed oceanic-arc suite whose underpinnings are not exposed. The basement of this early arc suite was most likely ophiolitic such as the complexes preserved in the Western Cordillera of Colombia (Bourgois et al., 1987).

Affinity of the Tobago terrane with other possible fragments of the accreted Mesozoic oceanic-arc in the southeastern Caribbean

The delineation of discrete tectono-stratigraphic terranes in the southern Caribbean evolved rapidly in the 1980s (e.g., Case et al., 1984; Speed, 1985). The early syntheses tended to include Tobago with the metamorphic belts of the Cordillera de la Costa of Venezuela or the Northern Range of Trinidad. However, Rowe and Snoke (1986) emphasized the overall volcanogenic nature of Tobago in constrast to the continental margin sedimentary character of protoliths for Northern Range metamorphic rocks. Furthermore, Wadge and Macdonald (1985) demonstrated that the metabasaltic rocks of the Sans Souci Formation of Trinidad were petrographically and geochemically distinct from the low-grade metavolcanic rocks of the TVG. These studies as well as this preliminary summary indicate no direct geologic linkage between the Mesozoic rocks of Tobago and Trinidad. Recent syntheses of the southeastern Caribbean indicate a major fault zone between northern Trinidad and Tobago (Robertson and Burke, 1989; Speed et al., 1989). Speed et al. (1989) have delineated this fault zone far to the west and suggest that it actually may outcrop on the Araya-Paria peninsulas of northeastern Venezuela (e.g., see Vignali, 1979). Near Carúpano, a northward-dipping thrust fault which separates a hanging wall of greenschist-facies, volcanogenic El Copey Formation from a footwall of metasedimentary Carúpano Formation (i.e., calcareous phyllite, metalimestone, graphitic-calcareous quartz-mica schist, and scarce metaconglomerate) has been delineated (Bladier, 1977; Vierbuchen, 1984). Lenticular serpentinite intercalations and numerous mesoscopic thrust faults suggest important tectonic disruption within the El Copey Formation (Schubert, 1971; Vierbuchen, 1984). Therefore, this thrust fault as well as the North Coast fault zone of Robertson and Burke (1989) may be the southern margin of the allochthonous Tobago terrane (Speed et al., 1989). Possible delineation of the Tobago terrane farther to the west is uncertain, for the Salazar fault truncates the low-grade metamorphic rocks of the Araya Peninsula and amphibolite facies rocks of the Manicuare Formation form the westernmost part of the Araya Peninsula (Schubert, 1971; Vignali, 1979). Nevertheless, Wadge and Macdonald (1985) and Frost and Snoke (1989) have argued that Tobago, the Villa de Cura klippe, the Netherlands Antilles, and various Venezuelan offshore islands (e.g., La Blanquilla) were members of a composite Mesozoic oceanic-arc terrane that was gradually accreted to northern South America, perhaps beginning as early as mid-Late Cretaceous (Pindell et al., 1988; Pindell and Barrett, in press). This correlation was principally based on petrochemical characteristics and scarce radiometric and paleontological age determinations. Much more detailed structural, geochemical, and geochronometric data are required to clearly understand how these various elements of the proposed allochthonous Mesozoic oceanic-arc were interrelated.

Metavolcanic units mapped as part of the Villa de Cura klippe possess clear petrographic affinities with rocks of the TVG. Perhaps the most obvious characteristic is the conspicuously clinopyroxene-phyric nature of the mafic metavolcanic rocks as emphasized by Shagam (1960) for the Villa de Cura Group and originally noted by Maxwell (1948) for the Bacolet Formation of the TVG. This distinctive hallmark is characteristic of many oceanic-arc volcanic suites throughout the western North American Cordillera (Snoke et al., 1982). Also equally distinctive is that clinopyroxene-rich ultramafic rocks are commonly associated with these metavolcanic rocks in the North American Cordillera, and detailed petrochemical studies of the clinopyroxenes in the volcanic and ultramafic rocks invariably suggest a distinct petrologic lineage (e.g., Irvine, 1973). This characteristic is also shared by both Tobago and the Villa de Cura klippe where mid-Cretaceous clinopyroxene-rich ultramafic rocks (Murray, 1972; Hebeda et al., 1984; Sharp and Snoke, 1988) have intruded and metamorphosed associated clinopyroxene-phyric metavolcanic rocks. Nevertheless, the blueschist facies metamorphism associated with penetrative deformation experienced by part of the Villa de Cura Group (Piburn, 1967) indicates an important difference in the petrotectonic history of the Villa de Cura Group as compared to the static prehnite-pumpellyite metamorphic history of the TVG. A clear understanding of why two apparently similar elements of the Mesozoic oceanic-arc experienced such different metamorphic and deformational histories requires more detailed comparative studies between the two regions.

Rocks units exposed on the Netherland Antilles and considered part of the accreted Mesozoic oceanic arc include the Curaçao Lava Formation, Washikemba Formation, Aruba Lava Formation, and Aruban batholith (Beets et al., 1984). The stratified and locally fossiliferous volcanogenic formations on an individual basis differ in stratigraphic age but when taken together range from mid-Albian(?) to Coniacian (Beets et al., 1984). The igneous crystallization age of the Aruba batholith has been estimated as 88.5+/-0.8 Ma based on a combination of Rb-Sr whole-rock data and K-Ar mineral ages (Priem et al., 1986). These data when combined with the previously enumerated geologic and age relationships of pre-Cenozoic rocks exposed on Tobago further emphasize the composite nature of the accreted Mesozoic arc. The olivine-phyric to plagioclase-pyroxene phyric lavas of the Curaçao Lava Formation record the accumulation of a great submarine, basic volcanic pile (more than 5 km thick) that may correlate with an Albian stage of primitive oceanic-arc growth (Beets et al., 1984; but see Donnelly et al., in press for another interpretation). This stage would be equivalent to much of the TVG. The apparently younger Washikemba and Aruba Lava formations record continued growth of this arc, but the Washikemba Formation includes more evolved magma types such as basaltic andesite (50-60 percent SiO_2) and rhyolite (70-75 percent SiO_2) (Beets et al., 1984). The youngest element of the oceanic-arc assemblage in the Netherland Antilles is the Aruba batholith. This intrusive plutonic complex ranges in composition from (quartz)-norite and quartz-hornblende gabbro to tonalite, and geochemical data from this complex appear to define a calc-alkaline trend (Beets et al., 1984). The Aruba batholith therefore represents a major late Cretaceous magmatic event in Mesozoic ocean-arc evolution, and as concluded by Beets et al. (1984), must pre-date accretion with continental South America.

Elements of the Mesozoic ocean-arc are probably also exposed on the various Venezuelan offshore islands (Dependencias Federales) including: Gran Roque, La Orchila, La Blanquilla, Los Hermanos, Los Frailes, and Los Testigos (Santamaria and Schubert, 1974). However, some radiometric ages (K-Ar, mineral ages) from these islands (e.g., La Blanquilla and Los Testigos) have yielded anomalously young, latest Cretaceous to early Tertiary dates (Santamaria and Schubert, 1974). These dates are difficult to integrate with most recent plate tectonic models for the southern Caribbean (e.g., Beets et al., 1984; Burke, 1988; Pindell et al., 1988), and we tentatively consider these dates as cooling ages unrelated to the initial age of igneous crystallization or metamorphism. However, Loubet et al., (1985) reported similar dates from Margarita Island and interpreted them as evidence of early Tertiary metamorphism. Much more detailed geologic mapping and coordinated geochronometric studies are necessary to make detailed correlations between the Venezuelan offshore islands and the other inferred parts of the Mesozoic oceanic-arc terrane.

Dredge hauls from the southern end of Aves Ridge indicate that this submarine feature is, at least in part, comprised of Mesozoic granitic rocks (Fox et al., 1971; Walker et al., 1972), and therefore, should also be included as part of the Mesozoic oceanic-arc terrane. These granitic rocks would seem to most logically correlate with the granitoid exposed on La Blanquilla (i.e., Garanton trondhjemite of Schubert and Moticska N., 1973). However, such a correlation is not straightforward as judged from the published geochemical analyses of the Garanton trondhjemite (Santamaria and Schubert, 1974) as compared to the petrographic and geochemical data derived from the dredged granitic rocks of the southern Aves Ridge (Fox et al., 1971; Walker et al., 1972). In particular, the granitic rocks from the southern Aves Ridge are more potassic and petrographically are granodioritic rather than trondhjemitic. Nevertheless, K-Ar mineral ages from the dredged granitoids have also yielded late Cretaceous to early Tertiary K-Ar mineral dates (89, 78, 67, 65, 58, 57 Ma)(Fox et al., 1971).

Granitic rocks ranging in composition from trondhjemite to tonalite to granodiorite were part of the Mesozoic oceanic-arc terrane. The apparently oldest representative of these quartz-rich granitoids is a dike-like intrusion of biotite +/- hornblende tonalite which is the youngest plutonic phase of the mid-Cretaceous Tobago pluton. Younger tonalitic rocks are also part of the late Cretaceous, calc-alkaline Aruban batholith and similar rocks apparently form a poorly studied igneous basement from Gran Roque to the southern end of Aves Ridge. These granitoids and the plutonic complexes which they are associated commonly intruded and metamorphosed a chiefly mafic volcanic sequence which ranged in age from mid-Albian to Turonian. Only on Tobago are rocks clearly older than Albian part of the Mesozoic oceanic-arc terrane (i.e., North Coast Schist), although analogous rocks may also be preserved in the Venezuelan offshore islands (Santamaria and Schubert, 1974).

Displacement history of the Mesozoic oceanic-arc terrane

The present geographic position of Tobago has been recognized as a geological anomaly for many years (Maxwell, 1948). Furthermore, the role of strike-slip displacement along the northern margin of South America is controversial. In some syntheses large strike-slip motion is inferred (Burke, 1988; Robertson and Burke, 1989; Erlich and Barrett, 1990), whereas other plate-kinematic models employ oblique collision with only modest strike-slip displacement (Speed, 1985). The resolution of these contrasting models is not completely apparent from the presently available data. However, an impressive set of diverse data argue for a Pacific origin for the Caribbean plate (Pindell et al., 1988; Pindell and Barrett, in press; Pindell, this volume), thereby implying significant displacement of the inferred fragments of the Mesozoic oceanic-arc from their site of origin. Furthermore, the oceanic-arc petrochemical character of all pre-Cenozoic rocks on Tobago (Frost and Snoke, 1989) clearly indicates an allochthonous history in respect to Tobago's present geographic position as part of the northeastern corner of the South American continental shelf. Such an allochthonous history suggests an important strike-slip component during the final emplacement and accretion of the Mesozoic oceanic-arc along the northern margin of South America. If Tobago, the Villa de Cura klippe, Aves Ridge, and the Aruba-Blanquilla arc were originally part of the "Great Arc of the Caribbean" (Burke, 1988), their accretion history and present geographic position may chiefly reflect a broad zone of transpressional strain between South America and the eastward migrating Caribbean plate which started with an initial collision in the mid-Late Cretaceous and continues to the Present.

CONCLUSIONS

The Mesozoic igneous and metamorphic rocks of Tobago, West Indies constitute a cross-section through a fragment of an allochthonous, composite oceanic-arc terrane (Fig. 5; Frost and Snoke, 1989). New geologic mapping coupled with petrochemical and geochronometric studies indicate:

1) the protolith for the oldest exposed part of the oceanic-arc terrane (NCS) is pre-Aptian and perhaps as old as Late Jurassic;

2) the NCS experienced pre-Albian penetrative deformation and lower greenschist facies metamorphism;

3) the Tobago plutonic complex and volcanic group are cogenetic and evolved in the mid-Albian;

4) ultramafic rocks of the plutonic suite intruded and dynamothermally metamorphosed the NCS forming an inverted, amphibolite-facies metamorphic aureole;

5) a mafic dike swarm widely intruded into the volcanic-plutonic complex and locally intruded the amphibolite-facies aureole and NCS;

6) the mafic dikes are chiefly mid-Albian and therefore were clearly coeval with the volcanic-plutonic suite, although a member of the swarm has also yielded an igneous crystallization age as young as 91 Ma;

7) the Mesozoic lithic belts of Tobago have been been attenuated and offset by brittle fault systems which were related both to the late stage emplacement history of the mid-Cretaceous plutonic complex as well as much later Cenozoic strike-slip faulting; and

8) the Cenozoic deposits on Tobago represent various shallow marine accumulations and their preservation therefore records tectonic uplift and/or sea level change.

ACKNOWLEDGEMENTS

Financial support for this research was provided by NSF grant EAR-8418139 awarded to A. W. Snoke and C. D. Frost. We thank Phyllis A. Ranz for her superb help in preparing the illustrations for this article. The critical review comments of David K. Larue were helpful in preparing the final version of the paper.

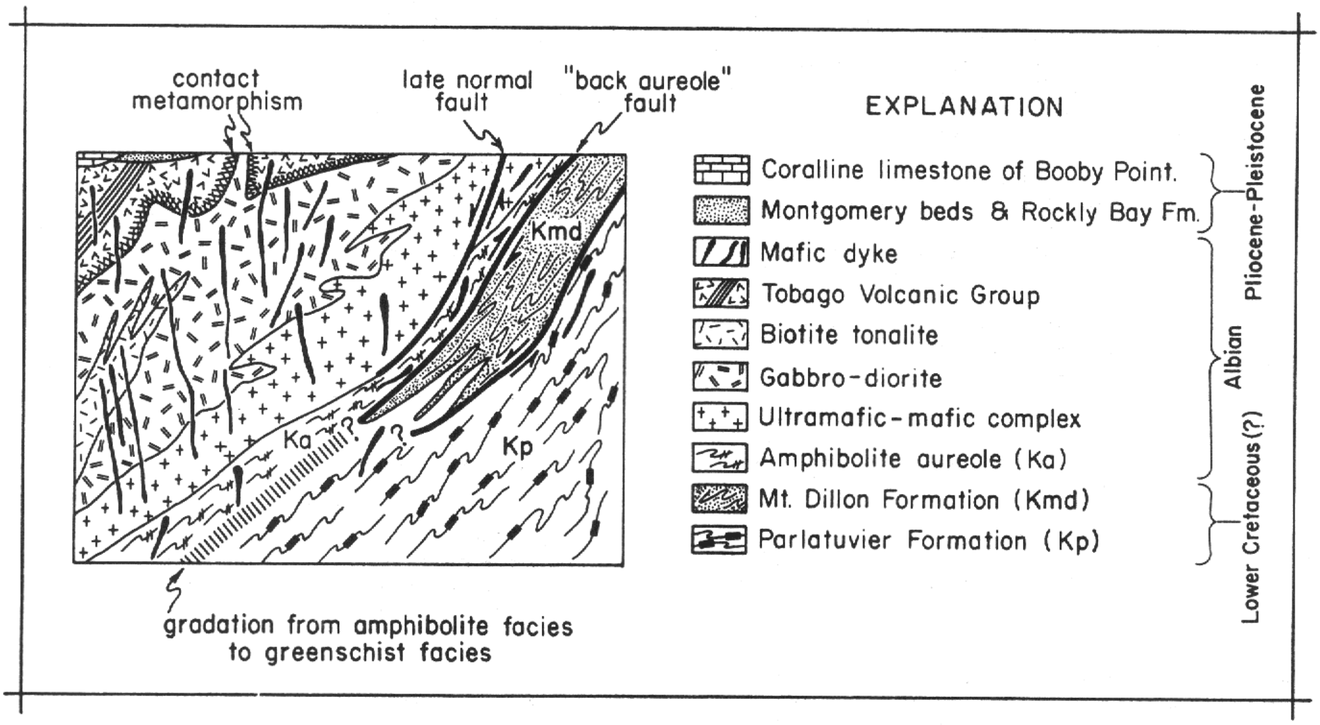

Figure 5. Schematic structural-stratigraphic diagram for Tobago, West Indies.

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